ARE BALLASTED ROOF SYSTEMS COOL?

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EXECUTIVE SUMMARY

A combined experimental and analytical study was initiated to quantify the energy savings of ballasted roofing systems and to compare their thermal performance to that of Cool Roof membranes. The experimental design was structured to evaluate how mass of three different stone ballast weights and one paver ballast affected heat flux into the building and the buildup of the membrane surface temperature in comparison to the controls, in this case both a black and a white single-ply membrane. Experimental work included the initial and subsequent occasional measure of reflectance and initial estimate of the emittance of the test samples, weekly organization of the temperature and heat flux data and the comparison of the ballast with the white and black membrane thermal performance. This work builds on the earlier work completed and published in "THE FIELD PERFORMANCE OF HIGH-REFLECTANCE SINGLE-PLY MEMBRANES EXPOSED TO THREE YEARS OF WEATHERING IN VARIOUS U.S. CLIMATES", which was also prepared by Oak Ridge National Laboratory for The Single-Ply Roofing Industry. This study investigated the reflectivity and thermal performance of single-ply membranes when exposed to the outdoor environment.

Modeling the stone for its thermal performance is one of the deliverables of the experimental work. The paver ballast with weight equal to that of the heavy stone sample was included to aid in developing the model. This model will allow the stone to be entered as a roof component into the DOE Cool Roof Calculator permitting the annual heating and cooling loads to be calculated for specific ballast configurations on roofs containing various insulation levels located in different regions of the country.

~~1.1~~ STONE REFLECTIVITY VERSUS STONE MASS AND THE IMPACT ON HEAT FLOW

After eight months of exposure in East Tennessee's climate, the white single-ply membrane control degraded in reflectivity by 15%, a similar rate as seen in the earlier study referenced above that showed the exposed single-ply membranes degraded thirty to fifty percent after three years of outdoor exposure. On the other hand, the paver ballast increased in reflectivity by 7% while the stone ballast reflectivity was assumed to remain unchanged based on results from the earlier study.

	Reflectivity Readings			Chart 1
	WHITE	STONE	PAVER	BLACK
INITIAL	0.78	0.21	0.52	0.06
8 MONTH	0.67	0.21	0.55	0.09
% CHANGE	(15)	0	7	50

The study evaluated the effects of mass on thermal performance by including three stone ballast weights of #4 stone at 10, 16.75, and 23.5 pounds per square foot, the 10-pound weight being the minimum allowed for ballasted systems. The paver weight was 23.5 pounds per square foot matching the heaviest stone weight. The membrane temperature and insulation heat flux data taken early in the study indicated that the 10-pound ballast weight produced thermal values about 30% higher than the white control. This is substantially better than what would be expected from the stone's reflectivity value of 0.21, which is 73% lower reflectivity than the white membrane (0.78) and closer to the black reflectivity of 0.06. As the mass of the stone was increased with no change in stone reflectivity, the thermal performance values proportionally reduced moving closer to the exposed white membrane system performance with the 24-pound ballast (stone or paver) having only 5% more heat transfer. Although the paver has a reflectivity of 0.51 compared to the stone value of 0.21, the paver and 24-pound stone samples had very similar thermal profiles with nearly equal high and low values indicating mass has a greater effect on thermal performance than reflectivity.

1.2 THERMAL PERFORMANCE OF BALLAST VERSUS REFLECTIVE MEMBRANES

The white membrane, with a reflectivity of 0.78 again proved to be an effective tool for deflecting the sun's energy from the building. However, some of this ability deteriorates over time, as the high reflectivity is lost due to air borne fallout, biological growth, and the weathering process. The study also showed that the ballast samples were successful in shielding the building from the sun's energy even though the ballast reflectivity was only 0.21. As the ballast mass increased, the thermal performance continued to improve. As stated above, the 10-pound ballast was within 30% of the thermal performance of the new white membrane while the 24-pound ballast was within 5%. The mass also delayed the time at which the maximum membrane surface temperature and heat flux were reached versus the white and black controls, a two to three hour delay dependent on the amount of the mass. This delay moves more of the cooling load into the off-peak hours of the day.

At the eight-month point in the study, the maximum temperature and heat flux values for the ballast has moved closer to the white thermal profile with the 24-pound ballast closely mimicking the white control. This is related to the loss of reflectivity of the white membrane, which is now 0.67, just above the 0.65 minimum reflectivity value required for a new product to be listed as an ENERGY STAR roofing product.

When the data are analyzed for only the daylight hours where cooling of a building is the major concern, the results at the start of the study showed the 24-pound stone providing the same level of performance as the white membrane while the paver provided slightly less savings. If one factors in the time delay in reaching the maximum temperature / heat flux, which moves more of the cooling load into the off-peak hours, the ballast offers an effective alternative to white membranes.

Sunny Day Maximum Temperature (°F) and Heat Flux [Btu/(h·ft²)] Values Chart 2

		WHITE	10#	17#	24#	PAVER	BLACK
INITIAL							
	TEMP	85	104	95	90	90	145
	HEAT FLUX	3	8.5	7	5	5	16.5
8 MONTH							
	TEMP	100	110	105	95	95	145
	HEAT FLUX	7	10	8	6	5	17

Sunny Day Average Temperature (°F) and Heat Flux [Btu/(h·ft²)] Values Chart 3

		WHITE	10#	17#	24#	PAVER	BLACK
INITIAL							
	TEMP	81	87	86	86	85	98
	HEAT FLUX	1.9	3.9	3.8	3.2	3.2	5.6
8 MONTH							
	TEMP	66	73	71	72	70	81
	HEAT FLUX	-1.1	.7	.4	.3	-.4	2.1

However, in the process of acting as a shield against the exterior conditions, the ballast mass absorbs some of this energy. With its mass far greater than that of a single-ply membrane, the ballasted roof takes longer to dissipate this energy even though it has emissivity values equal to those of the single-ply membranes. This, in turn, keeps its average temperature and heat flux above those of the white membrane over a 24-hour period. In the heat of the summer this is a disadvantage to the ballast system. However, as the outside temperature moderates both in the spring and fall, this slower reaction to both high and low temperatures dampens the heat flow through the roof and stabilizes the heating and cooling loads in the building under a ballasted system.

1.3 WILL BALLAST QUALIFY AS AN ENERGY STAR ROOFING PRODUCT?

A roofing product that has a “new” minimum reflective value of 0.65 and a three-year aged value of 0.50 or greater (after washing) qualifies to be listed as an ENERGY STAR product for use on low-sloped roofs. The ballast used in the study does not meet the current ENERGY STAR criteria. The study indicates that a ballasted system with a reflective value of only 0.21 does perform at the same level of thermal performance as the rated ENERGY STAR products. There is also an indication that the dampening effect of the ballast may actually offer equal or better performance over a full day, month, or year of operation. More information will be developed over the next five months to try to determine whether or not ballast performs as well as currently listed ENERGY STAR roofing products.

Essential to this effort is the ability to model the thermal performance of the ballasted systems with available tools. Specifically, thermal properties are needed for use in the transient heat conduction equation. Preliminary work has been done with a program that does the inverse: it uses the transient heat conduction equation to predict thermal properties to fit the measurements of heat flux and temperature. The program had difficulty converging with the data for the 10-pound and 16.75-pound ballasts during the summer months when convection effects in thin layers of stone could be expected. Early on in the project and now again after nine months, analysis with the program is showing some hope of predicting thermal properties consistently from week to week.

Best estimates, so far, puts the thermal conductivity of the stone at 0.3 to 0.4 Btu/(h·ft·°F) and volumetric heat capacity (product of density and specific heat) at 19 to 21 Btu/(ft^3·°F). The corresponding estimates for the paver are 1.45 to 1.65 Btu/(h·ft·°F) and 23 to 25 Btu/(ft^3·°F). With the measured thicknesses of the stone and paver, these thermal conductivities yield R-values of 0.3 to 0.4 h·ft^2·°F/Btu for the 10-pound stone, 0.5 to 0.6 for the 16.75-pound stone, 0.6 to 0.8 for the 23.5-pound stone and 0.10 to 0.11 for the 23.5-pound paver. The ballasts form low R-value, high thermal mass systems.

Until a consistent picture emerges of the thermal properties, work cannot be started with the modeling of the thermal performance of the systems. Modeling will use the thermal properties to predict the heat flux through the fiberboard insulation in each test section. Comparison to the measured heat flux will validate the model or, if agreement is affected consistently by convection effects in the thin stones, the comparison will calibrate the model. A validated or calibrated model permits prediction of thermal performance in different locations with roofs having typical insulation R-value. The test roofs had minimal insulation R-value in order to maximize the sensitivity of the measurements to differences in the ballast properties.

2. INTRODUCTION

In warm desert climates, structures were often made of thick, sand-colored adobe walls before modern construction materials were available. These walls had substantial thermal mass, which helped to isolate the inside of the building from the outside environment. In many parts of the United States, older structures were made with thick, stone walls also providing some protection from the heat of a summer day by absorbing the sun's energy in the wall mass. On the other hand, light colored materials protect the building by reflecting the sun's energy, reducing the energy load on a building. Temperature measurements made at the Buildings Technology Center (BTC) show that, on a sunny day, a highly reflective roof surface can be as little as 3°C (5°F) warmer than ambient air temperature, while a dark absorptive roof surface can be upwards of 40°C (75°F) warmer. This knowledge has accelerated the use of roofing products that offer smooth, highly reflective surfaces to reduce the energy needs for cooling the building. Where do ballasted systems with irregular earth tone colored stone surfaces fall in comparison to new "high-tech" exposed membrane systems? Some information on ballasted system thermal performance was obtained in the original study, "THE FIELD PERFORMANCE OF HIGH-REFLECTANCE SINGLE-PLY MEMBRANES EXPOSED TO THREE YEARS OF WEATHERING IN VARIOUS U.S. CLIMATES", but was of secondary interest since the primary focus was on the exposed membranes. The ballast weight was not measured accurately so the data could not be quantified. Trends indicated that the ballast was shielding the building from the sun's heat to some extent helping to justify the initiation of the current study.

~~2.1~~ BRIEF HISTORY OF BALLASTED ROOFING SYSTEMS

Ballasted systems entered the roofing market in the early 1970’s. The stone used with these systems is different from the traditional quarter inch chip or smaller stone used with built-up and modified bitumen roofing. With these last two systems the small stones are partially imbedded into the topcoat of asphalt to protect the asphalt (same applies to coat tar based systems) from the harmful rays of the sun. The stone used as ballast for single ply systems is large in size, #4 (.75 to 1.5 inch in diameter) and larger stone. Ballast comes in other configurations such as concrete or rubber pavers. Ballast is applied in loadings from 10 (the minimum) to over 24 pounds per square foot. So with the loose-laid ballasted roof system, the contractor places all the components of the roof system, including the thermal barrier and insulation, unattached on the roof deck. The membrane is also loose-laid except for attachment around the perimeter of the building and at roof penetrations. The ballast is then placed on top of the membrane weighting down all the components to hold them in place. This technique eliminates the use of copious fasteners that are used to hold the roofing components in place, which in turn minimizing thermal bridging. This also eliminates the need for adhesives to attach the membrane to the roof deck substrate. Thus, the ballasted method can greatly reduce the installed cost of the roof system as well as the time to install it. In addition, this ballast is basically fire proof providing Class A (top rating) fire protection for the building that is under the system. EPDM takes great advantage of this construction with its ability to be factory-made in large sheets (up to 10,000 sqft), further reducing the labor and, in turn, the installed cost of the roof system while improving overall quality. These benefits allowed this system to become a major factor in the roofing marketplace.

Ballast is also used with the inverted - protected roof system where the roof system is built “upside down.” A protective course maybe placed over the deck. The membrane is then laid down, followed by the insulation, a filter fabric and the ballast. The ballast often used in this application is pavers because this system is often used in applications where there will be pedestrian traffic. Plaza decks and roof top terraces are a few examples. The paver offers a trafficable surface with the insulation acting as a thermal protection layer and a shock absorber for the waterproofing system below it. In some applications, the paver is made from rubber yielding a play-exercise surface on the roof. Another form of ballast is mixed soil media and plants to form a roof garden with unique aesthetic appeal and performance characteristics such as storm water management.

Because of the inherent simplicity of ballast systems, early proponents focused mainly on expansion into the market. During this early period, there was little technical information available on one design consideration, namely, how to design a ballasted roof system to resist the destructive powers of the wind. This led to a number of wind performance issues toward the end of the 70’s and into the early 80’s. This, in turn, energized the industry to find the answers for designing a ballasted system for specific wind zones. Extensive wind tunnel work was conducted with thorough verification of the modeling through field observations, all leading to the development of the SPRI RP-4 national standard entitled “Wind Design Standard for Ballasted Single-Ply Roofing Systems”. This standard outlines design procedures for ballasted systems for addressing wind loads on various building designs in locations across the country. This standard has proven its merits with these systems surviving major storm events including the hurricane season of 2004. The development of this standard increased confidence in the ballast system.

In recent years, new "high-tech" roofing membranes, offering highly reflective surfaces, have become the "new rage" of the industry. These membranes are used in fully adhered and mechanically fastened roof systems to take advantage of the reflective property of the membrane. With these systems offering aesthetically pleasing roofs that assist in saving energy for the building owner, ballast systems now seem a little old fashioned and out of step with the times. Is this truly the case or are there hidden attributes to the ballasted system that have not been identified?

2.2 GEORGIA TECH INFRARED STUDY

The paper titled "Georgia State University Roof Temperature Study" written by Marty Waterfill, CSI and Patrick Downing, RRC, CDT evaluated techniques to measure roof surface temperatures for buildings on the campus of Georgia State University. They compared results from a hand-held infrared thermometer to a high-resolution multispectral sensor mounted in an aircraft that did flyovers of the buildings. The roof types that were measured were built-up and modified bitumen with different surfacing as well as ballasted EPDM. The data in the paper were very limited so items such as surface reflectivity was not supplied except for the three modified bitumen roofs that had their roof surface color identified. Even so, Table 1 shows that the ballasted systems had the lowest surface temperature readings of the group of roofs. This information added additional support for the current study on ballast thermal performance.

Table 1. Roof surface temperatures from the Georgia State University Roof Temperature Study

Roof Type	Ave Temp
CTP BUR	113
CTP BUR	115
CTP BUR	146
MB – white granules	138
ASP BUR	112
CTP BUR	136
CTP BUR	146
CTP BUR	137
CTP BUR	151
CTP BUR	123
MB – white granules	150
CTP BUR	132
EPDM BALLASTED	117
EPDM BALLASTED	111
EPDM BALLASTED	124
MB – white granules	141
ASP BUR	118
EPDM black surface	152
ASP BUR	150

Roof Family	Ave Temp
CTP BUR	133
ASP BUR	126
MB Granules	143
EPDM Ballast	117
EPDM Black Surface	150

Note: CTP is Coal Tar Pitch, ASP is Asphalt, MB is Modified Bitumen multiply.

~~2.3~~ MEMBRANE REFLECTIVITY VERSUS BALLAST THERMAL MASS

The river wash stone used with the ballasted system, when laid over a substrate, produces a rather irregular surface that scatters any reflected light in many directions. Some light will reflect off one stone only to strike other stones, leading to multiple absorptions and low reflectivity. Stone comes in many colors from dark browns and reds to bright white. These stone types will produce reflectivity values from below 0.20 to over 0.40 however, none will qualify as an ENERGY STAR roof for low-slope roof applications.

Pavers have flat surfaces that can be finished to any surface smoothness and color. Hence, there is an opportunity to produce products with reflective values from below 0.2 to well above 0.65, the value at which a roofing product qualifies as an ENERGY STAR product. However, there is a penalty to achieve this higher reflectivity for it takes additional manufacturing procedures to produce the smooth or glazed surfaces greatly increasing the cost of the pavers. The paver that was used in this study had an initial reflectivity of 0.52, which is below the ENERGY STAR threshold.

Ballast mass is a factor independent from either surface color or finish. Ballast with high thermal mass requires considerable energy to raise its temperature, therefore, absorbing much of the sun's energy and shields the building from it. The unknown is just how effective ballast is in shielding this energy when its mass is in the ten to twenty four pounds per square foot range and comes in different forms, both stone and paver. The stone with its open structure has air cavities while the paver is a dense material. How do they affect thermal performance in comparison to Energy Star listed reflective products?

3. FIELD TEST FACILITY

3.1 ROOF THERMAL RESEARCH APPARATUS

The Roof Thermal Research Apparatus (RTRA) at the Oak Ridge National Laboratory located in Oak Ridge, Tennessee was constructed in the late 1980's for documenting the effects of long-term exposure of small, low-slope roof test sections to the East Tennessee climate. The RTRA has four 4 ft by 8 ft openings in its roof to receive different instrumented low-slope roof test sections. Each 4 ft by 8 ft test section may be divided into multiple areas. The original use of the RTRA showed in-service aging effects with CFC and alternative blowing agents for polyisocyanurate foam insulation boards in roofs covered by black and white membranes. Each test section was divided into two 4 ft by 4 ft areas, one with a black membrane and the other with a white membrane. In the late 1990's, the RTRA was used to document the thermal performance of low-slope roofs coated with reflective coatings. Each test section was divided into 2 ft by 2 ft areas with as many as eight different surfaces on a test section. Currently, three of the four test sections are being used for the ballast systems project. Each test section is divided into two 4 ft by 4 ft areas. One contains the ballast systems for the 10 pound and 16.75 pound tests. The second contains the 23.5-pound tests, both stone and paver. The third contains the control systems, one with a black membrane and the other with a white membrane.

The fourth test section continues to be used to show the in-service aging effects for polyisocyanurate foam insulation boards, now with third generation blowing agents. Figure 1 is a photograph of the RTRA that shows the entire building including the weather station.

Figure 1. Roof Thermal Research Apparatus with weather station

A dedicated data acquisition system is housed inside the RTRA. It acquires the outside temperature and relative humidity and the wind speed and direction 10 ft above the roof of the RTRA. The total horizontal solar insolation and the total horizontal infrared radiation are measured at the top of the railing in Figure 1. There are also many dedicated input channels for thermocouples and for millivolt signals, such as those produced by heat flux transducers. Jack panels are conveniently located under the test sections on the inside of the RTRA walls to make for short lead wires from the test sections to the jack panels. Data are acquired under control of a database that is specific to each experiment. The database instructs the data acquisition program as to what data to acquire and how often. Most channels are polled every minute. Data are stored in a compressed historical record. For ongoing experiments, averages every 15 minutes of all variables are written weekly to a spreadsheet. Special reports can be generated for further detail on time dependency down to the frequency in the historical record.

3.2 BALLAST PROJECT TEST SECTIONS

Figure 2 is a photograph taken on top of the RTRA that shows the three test sections being used for the ballast systems project. The controls are in the foreground and the ballast systems are in the background beyond an uninstrumented area for unmonitored exposure of materials. To begin construction of the ballast systems, pavers 2-in. thick and 2 ft square were weighed on a scale to determine their weight per unit area. It was 23.5 pounds per square foot. Three of the four pavers required for a 4 ft square test section were sawed in half in order not to have any seams at the center of the paver test section. A whole paver occupies the center and halves complete it. The required weight of stone in the test area to achieve the same loading as the pavers was determined for the heaviest stone. The lightest stone ballast loading was set at 10 pounds per square foot, which is the minimum allowed for a ballast system, and it did supply 100 percent coverage of the membrane. The third paver was set at the average of the heaviest and lightest. Buckets were used to carry the #4 stone from the scale to the roof of the RTRA where it was distributed inside frames to confine the ballast to its assigned area. Exactly enough stone was used to achieve the 10, 16.75, and 23.5 pound per square foot loadings. Separate determinations were made of the weight of stone to exactly fill a bucket and the volume of the bucket. This yielded a density of 92.4 lb/ft^3 for the stone. Dividing each loading by the density of the stone yielded average thicknesses of 1.30, 2.18 and 3.05 in., respectively, for the three stone ballast systems. Due to the nature of the stone, the thicknesses vary over the area of each stone test section.

Figure 2. Test sections configured for the ballast tests

3.3 INSTUMENTATION OF THE TEST SECTIONS

The instrumentation for each 4 ft by 4 ft test section is shown in Figure 3. The metal decks are exposed to the conditions inside the RTRA, which is maintained year round between 70°F and 75°F by an electric resistance heater and a small through-the-wall air conditioner. The membranes, in the case of the unballasted controls, or the top surfaces of the ballast, for the other test sections, are exposed to climactic conditions. Thermocouples on the decks and at the top of the test sections monitor the direct response to the imposed conditions. Additional thermocouples are at the internal interfaces. Wood fiberboard insulation 1.5 in.-thick is used to maximize sensitivity to differences among the test sections. At the interface between 1 in.-thick and 0.5 in.-thick pieces of insulation, a heat flux transducer (HFT) is embedded in the top of the thicker insulation board. Each HFT was especially calibrated in the same configuration. Thermocouples are deployed at the level of each HFT, 6 in. and 12 in. from its center to monitor if there is any significant heat flow in the horizontal direction. Thermocouples at the other levels are 6 in. from the center of the test section.

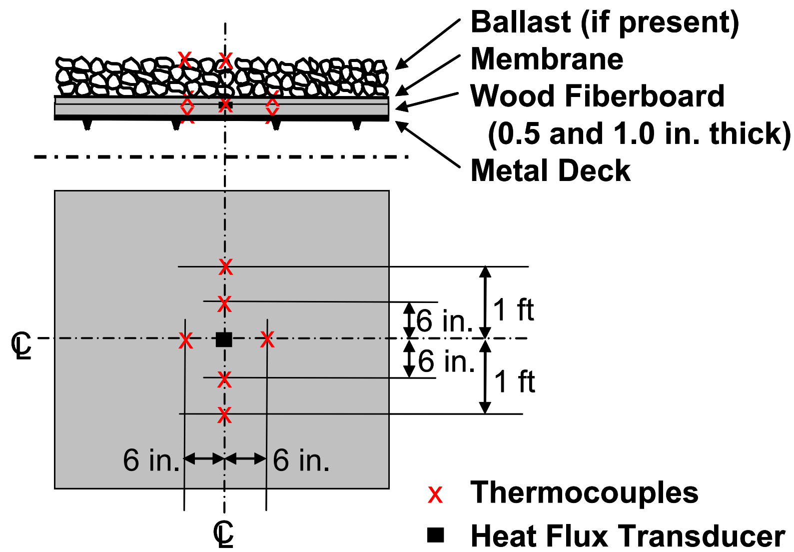

Figure 3. Thermocouple and heat flux transducer placement relative to the center of each 4 ft by 4 ft test section

The irregular upper surface of the stone-ballasted test sections presents a special challenge for monitoring surface temperature. Figure 4 shows the scheme that was adopted. Aluminum wire is strung across the middle of the frame from side to side in both directions. Thermocouples are attached to the wires with plastic wire ties. The lead wire between each measuring junction and its nearest wire tie is bent to hold the measuring junction against a stone at the top of each test section. At the top of the paver-ballasted test section a shallow hole was drilled into the top of the central paver, about 6 in. from its center, and the thermocouple was epoxied in place with its measuring junction touching the bottom of the hole.

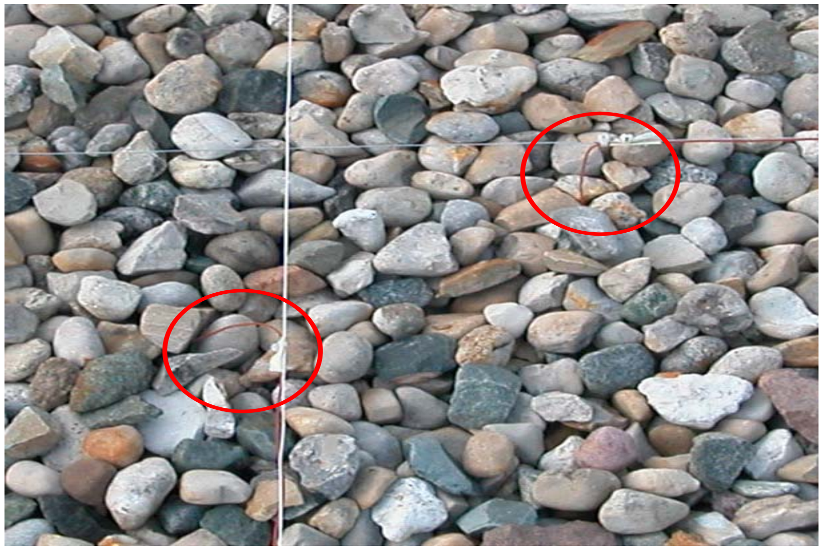

Figure 4. Thermocouple measuring junctions placed against pieces of stone at the top of the stone-ballasted test sections

A property of primary interest for modeling thermal performance of roofs is the solar reflectance of the roof surface. It was measured for the surfaces of the test sections with two different techniques. For the smooth surfaced controls and the relatively smooth surfaced pavers, a Devices & Services solar spectrum reflectometer was taken onto the RTRA and used according to ASTM C 1549-02, Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer. Solar reflectance for the white TPO membrane at five locations on its surface averaged 0.779 for measurements on 3/12/2004 and decreased to 0.666 on 9/27/2004. For the black EPDM membrane, the average solar reflectance at five locations was 0.060 on 3/12/2004 and 0.090 on 9/27/2004. Measurements on the central full-sized paver yielded 0.516 on 3/12/2004 and 0.553 on 9/27/2004. Seven locations were measured in March and five in September on the paver.

For the stone-covered test sections, a Davis Energy Group roof surface albedometer was taken onto the RTRA and used with guidance from ASTM E 1918-97, Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-Sloped Surfaces in the Field. The albedometer measures the solar reflectance of a surface as the ratio of the output of a solar spectrum pyranometer when inverted (facing downward toward the surface) and facing upward during an interval of constant solar irradiance. The area of the ballasted test sections is only 4 ft by 4 ft, not the 4 m by 4 m (13 ft by 13 ft) recommended in E 1918 for use of the instrument. In order to minimize the effect of shadows from the assembly on the test section during use of the albedometer, a standard 50 cm (20 in.) height of the sensor above test sections is specified. It is achieved by the support stand that is part of the assembly.

Because of the relatively small size of the ballasted test sections, the standard height was relaxed. A special guide was made to achieve heights of 10 in., 15 in., and 20 in. above the surfaces while manually holding and leveling the pyranometer and its support arm long enough for a steady response from the millivolt meter that monitors the output of the pyranometer. Apparent solar reflectance was measured at these three heights. Shape factor algebra yielded the fraction of the pyranometer's view taken up by the stone. The remainder is surroundings at some constant but unknown reflectance. The reflectance of the surroundings was varied by trial-and-error until the reflectance of the stone was constant with height of the pyranometer above the surface. It was concluded that the solar reflectance for the stone ballast is 0.21 ± 0.01. Within the precision, it is the same value obtained during the SPRI study and indicates that the reflectance of the stone is constant. Precision better than ± 0.01 would require an improved apparatus for measuring reflectance at small heights.

A property of secondary interest for modeling thermal performance of roofs is the infrared emittance of the roof surface. It is difficult to measure for thermally massive systems, especially the irregular surfaces of the stone-ballasted systems. In general, non-metallic surfaces have infrared emittance near 0.9. This value is assumed to apply to all the test sections in the ballast system study and has been verified often in the SPRI study for single-ply white and black membranes.

To model the thermal performance of the ballasted systems with available tools, thermal conductivity and volumetric heat capacity (product of density and specific heat) of the ballast are needed for use in the transient heat conduction equation. Preliminary work has been done with a program that does the inverse: it uses the transient heat conduction equation to predict thermal properties to fit the measurements of heat flux and temperature. The program had difficulty converging with the data for the 10-pound and 16.75-pound ballasts during the summer months when convection effects in the stone could be expected. Early on in the project and now again after nine months, analysis with the program is showing some hope of predicting thermal properties consistently from week to week.

Best estimates, so far, put the thermal conductivity of the stone at 0.3 to 0.4 Btu/(h·ft·°F) and volumetric heat capacity at 19 to 21 Btu/(ft^3·°F). The corresponding estimates for the paver are 1.45 to 1.65 Btu/(h·ft·°F) and 23 to 25 Btu/(ft^3·°F). With the measured thicknesses of the stone and paver, these thermal conductivities yield R-values of 0.3 to 0.4 h·ft^2·°F/Btu for the 10-pound ballast, 0.5 to 0.6 for the 16.75-pound ballast, 0.6 to 0.8 for the 23.5-pound ballast and 0.10 to 0.11 for the 23.5-pound paver. The ballasts form low R-value, high thermal mass systems.

Until a consistent picture emerges of the thermal properties, no work can be done with modeling the thermal performance of the systems. Modeling will use the thermal properties to predict the heat flux through the fiberboard insulation in each test section. Comparison to the measured heat flux will validate the model or, if agreement is affected consistently by convection effects in the thin stones, calibrate the model. A validated or calibrated model permits prediction of thermal performance in different locations with roofs having typical insulation R-value. The test roofs had minimal insulation R-value in order to maximize the sensitivity of the measurements to differences in the ballast properties.

4. EXPERIMENTAL RESULTS

The ballast study went live on March 12, 2004 with the start of the data collection that has continued through 36 weeks at this point. Figure 5 shows the week results for the average heat flux either into the build (positive) or out of the building (negative) for a twenty-four hour period. The three distinct assemblies, black surfaced membrane, ballast, and the white surfaced membrane are visible in the figure. As the study moved into the summer period, the ballasted configurations began to show some separation as the heavier systems provided better shielding of the building from the heat. As the study moved into the fall the white assembly began to move closer to the ballasted systems because of the deterioration of its reflectivity due to aging, however, its reflective value of 0.67 is still above the ENERGY STAR minimum requirement of 0.65. As the assemblies move into the first cold weather of the study, the thermal curves all collapse together.

In Figure 6, the weekly heat flux averages are shown for just the daylight hours, the period when the white membrane is reflecting the suns energy reducing the air conditioning load. As with Figure 5, this figure shows the same distinct curves for the assemblies with the black surface having the greatest heat flux, the white the least and the ballast in the middle. There is greater separation between the four ballast assemblies in this scenario as the mass factor has a great affect as the heat develops in this part of the day. However, as the assemblies move into summer, the 24-pound ballast assemblies begin to match the white membrane for heat flux and by fall has equaled or bettered the white membrane. As the first of the cold weather hits, the data duplicates Figure 5 with all but the black membrane collapsing together.

Figures 7 through 12 show the thermal data collected for each assembly for a twenty-four hour time period. There is a set of two charts, one membrane temperature and one for heat flux, for a specific day in the spring, summer and fall. Figure 7 and 10 are spring readings taken on April 5 when everything is new. Starting at sunrise, the membrane temperature climbs with the white peaking first (85 degrees F) followed closely by the 24-pound paver and stone assemblies, which peak slightly higher at 90 degrees F. Next to peak is the 17-pound ballast followed by the 10-pound ballast and then at a considerably higher temperature the black membrane at 145 degrees F. The chart shows the ballast variables are close to the white membrane in peak temperature reached but offer one unique property in that as the weight increases the time the peak temperature is reached is delayed. This delay can be in the range of three hours pushing more of the cooling load into the off-peak hours of the day saving both energy and dollars.

Figures 8 and 11 show the readings taken during the summer period where the 24-pound paver and stone are now performing basically equal to the white membrane for peak temperature with the 17 and 10 pound ballast peaking just over it.

The fall readings shown in Figures 10 and 12 now show the 24-pound assemblies peaking in temperature first with the white membrane peaking at a higher temperature. The 17-pound assembly is peaking at a temperature that is basically the same as the white. At the fall reading, the white membrane is still above the ENERGY STAR minimum reflective value of 0.65 indicating that the ballast systems do perform as a Cool Roof.

An additional item to note is the reflectivity for the 24-pound paver is 0.51 while the 24-pound of stone is 0.21 yet the thermal curves fall pretty much on top of each other during the daylight hours indicating that after a certain weight, mass becomes the controlling factor instead of reflectivity for shielding the building. Yet at other times of the day, the paver and ballast thermal curves separate showing they are not the same making it more difficult to model the ballast for use in the energy model calculators. There is some indication that the ballast may have two R-values depending on whether heat is moving into or out of the building.

5. ITEMS TO BE COMPLETED IN THE STUDY

The following items in the study are to be completed:

a. Complete the data collection
    i. For one fully year
    ii. Through the second summer
b. Model the stone characteristics for use in the energy calculators
    i. Thermal conductivity
    ii. Volumetric heat capacity (product of density and specific heat)
c. Quantify the ballast performance against the ENERGY STAR requirements
d. Determine the value of the ballast time-delay for energy cost savings.

6. REFERENCES

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FIGURES

[NOTE: Preliminary results can show the observed differences among the test sections with some preliminary conclusions. In addition to the behavior on sunny days already presented to SPRI by André Desjarlais, which shows peak shaving and peak shifting due to ballast, the weekly behavior of heat flux may be of interest. Here are two figures that show it so far in the project.]

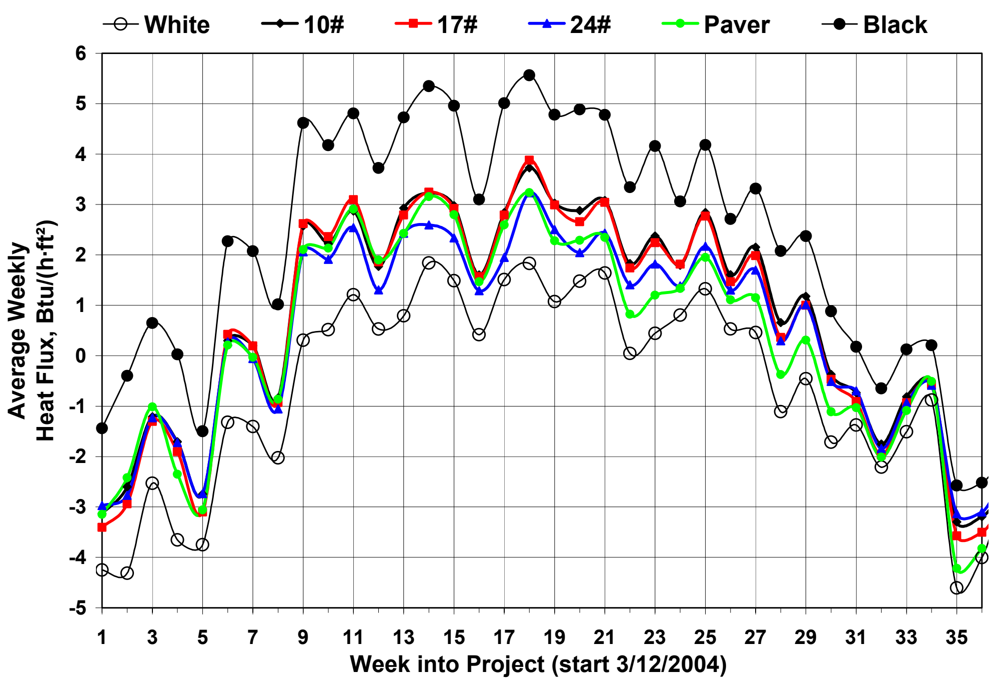

Figure 5. Average weekly heat flux through the insulation under the ballast and the control membranes through week 36 of the project

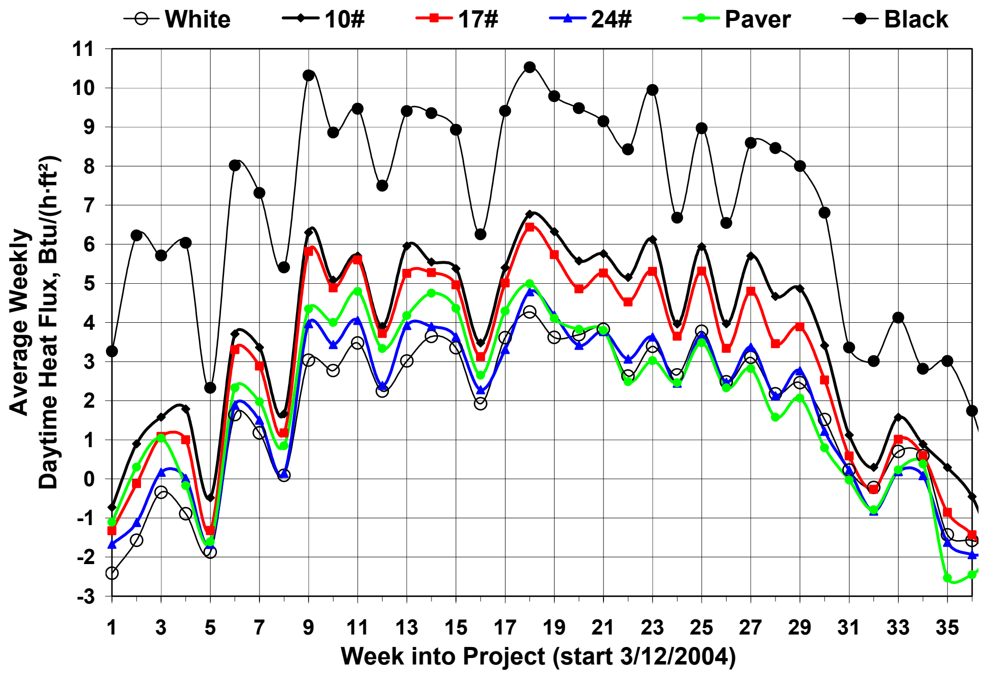

Figure 6. Average weekly heat flux (daytime only) through the insulation under the ballast and the control membranes through week 36 of the project

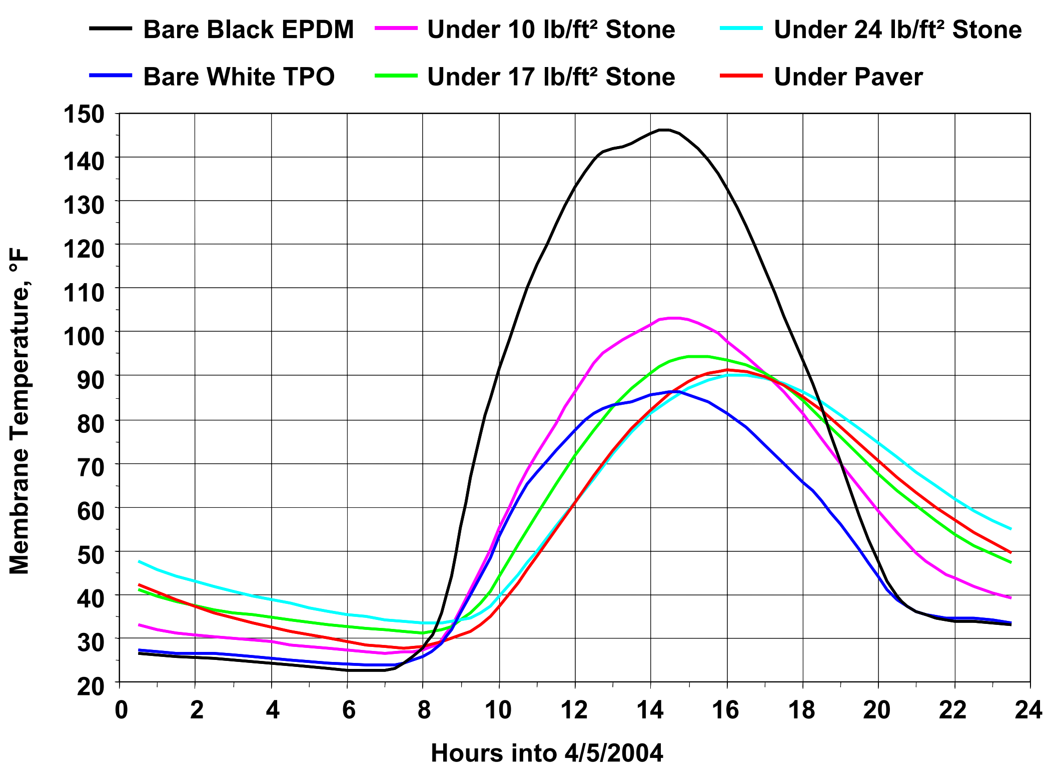

Figure 7. Membrane temperatures for a clear spring day in East Tennessee

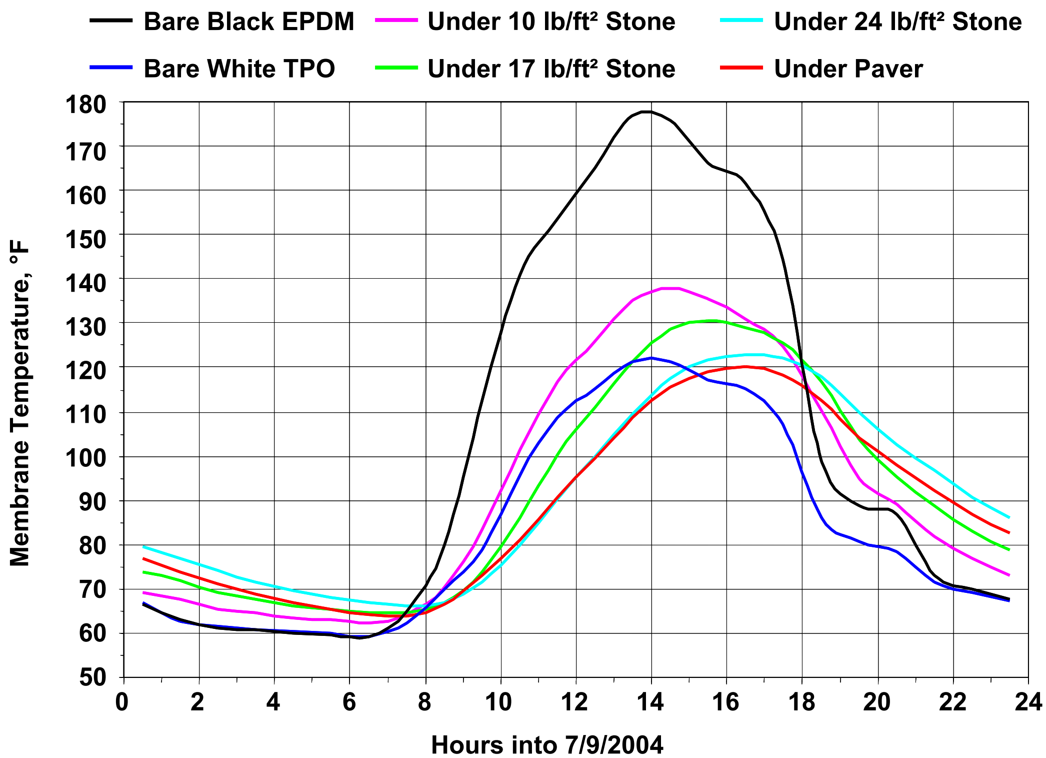

Figure 8. Membrane temperatures for a clear summer day in East Tennessee

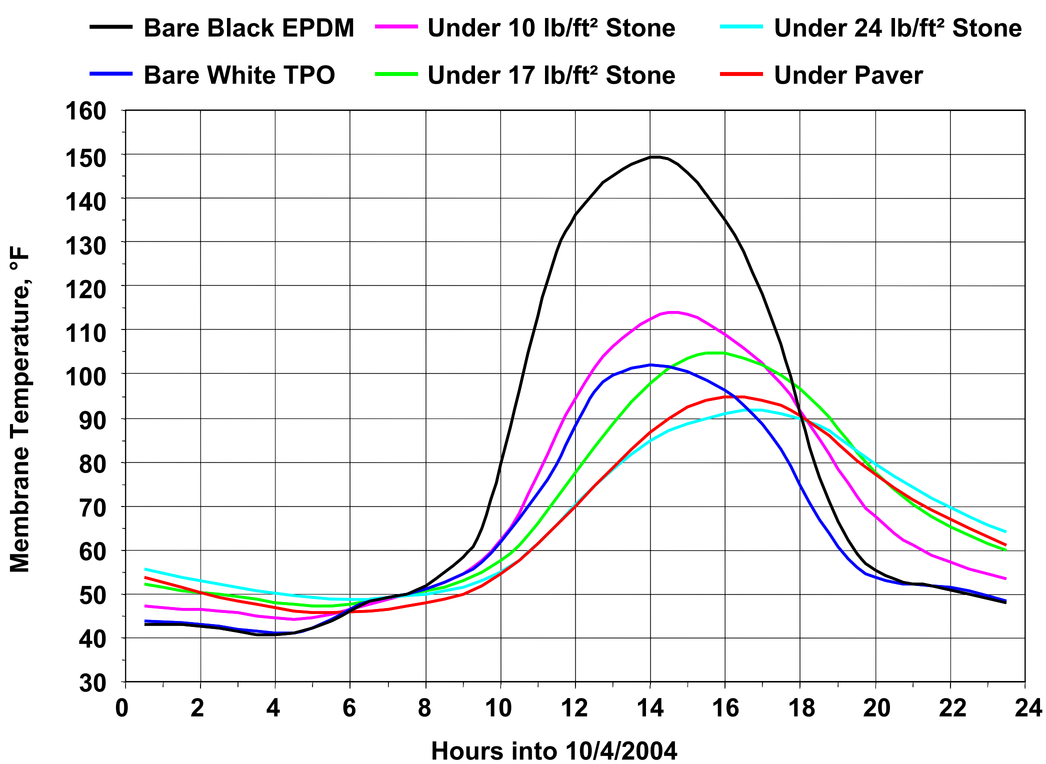

Figure 9. Membrane temperatures for a clear fall day in East Tennessee

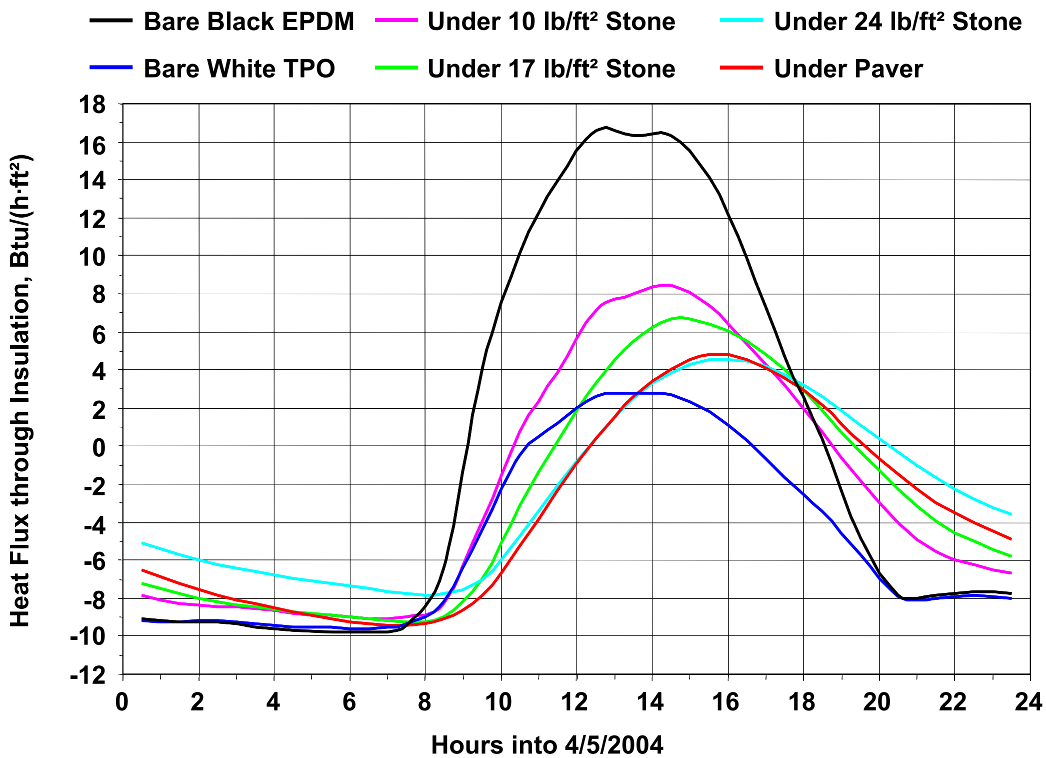

Figure 10. Heat fluxes through the insulation for a clear spring day in East Tennessee

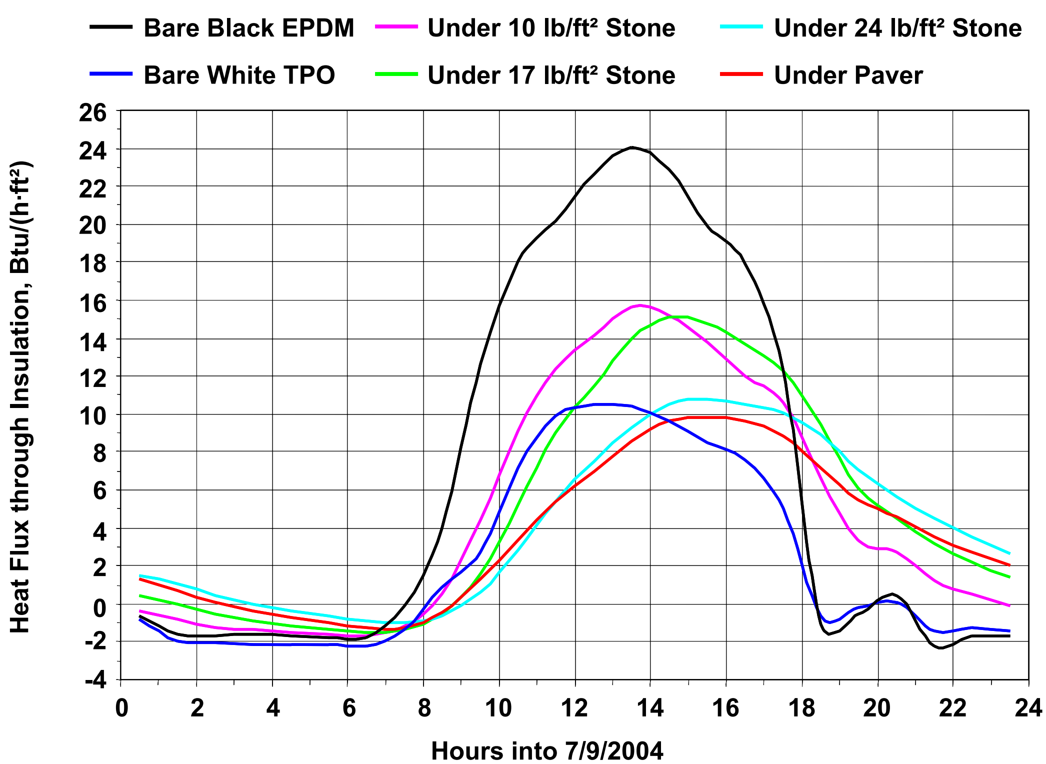

Figure 11. Heat fluxes through the insulation for a clear summer day in East Tennessee

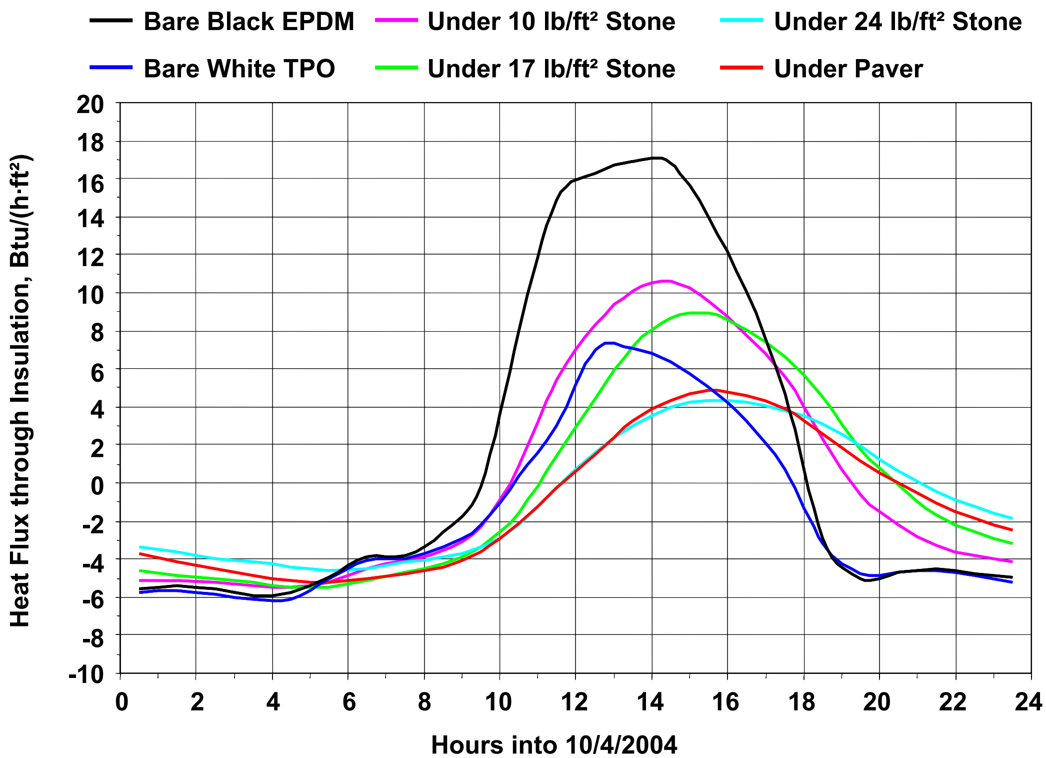

Figure 12. Heat fluxes through the insulation for a clear fall day in East Tennessee

Table 2. Membrane reflectivity changes during the first six months of the project

Test section	Covering or loading	Thickness (in.)	Solar reflectivity	
			3/12/2004	9/27/2004
Black control	Bare EPDM	0.045	0.06	0.09
White control	Bare TPO	0.050	0.78	0.67
10# stone	10.0 lb/ft² on EPDM	1.3	0.22	Not done
17# stone	16.75 lb/ft² on EPDM	2.2	0.22	Not done
24# stone	23.5 lb/ft² on EPDM	3.1	0.22	Not done
Paver	23.5 lb/ft² on EPDM	2.0	0.52	0.55